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Interpretation of Magnetic Anomalies in Salihli (Turkey) Geothermal Area Using 3-D Inversion and Edge Detection Techniques

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***Abstract*—There are numerous geophysical methods used to investigate geothermal areas. The major purpose of this magnetic survey is to locate the boudaries of active hydrothermal system in the South of Gediz Graben in Salihli (Manisa/Turkey). The presence of the hydrothermal system had already been inferred from surface evidence of hydrothermal activity and drillings. Firstly, it was necessary to convert the total field anomaly into a pseudo-gravity anomaly map. Then the geometric boundaries of the structures were determined by applying a MATLAB based software with 3 different edge detection algorithms. The exact location of the structures were obtained by using these boundary coordinates as initial geometric parameters in the inversion process. In addition to these methods, reduction to pole method was applied to the data to achieve more information about the location and shape of the possible reservoir. As a result, the edge detection methods were found to be successful in the field data sets for delineating the boundaries of the possible geothermal reservoir structure. The depth of the geothermal reservoir was determined as 2,4 km from 3-D inversion and 2,1 km from power spectrum method. The results of this study also suggest that the Salihli geothermal prospect extends further to the south of a resistivity boundary delineated from previous studies.**

***Index Terms*—3-D inversion, edge detection, geothermal, Salihli**

I. Introduction

The demand for geothermal energy is increasing due to its clean, sustainable use as a renewable resource. Geothermal energy has been produced by using the steam or hot water collected underground at high temperatures and pressures for the generation of electric power in conventional steam turbines, and by the direct use of the heat content of the resources in heat exchangers in industrial or domestic utilizations,such as in hot springs and spas, fishing and farming industry, and heating individual buildings and as well as the entire district. Geothermal energy is the accumulation of heat energy as hot water within hot and dry rocks, steam or gases under pressure within the earth's crust at various depths. The change in physical properties of rock with temperature may be determined using electrical, electromagnetic, gravity, magnetic, seismic, radiometric and well-logging geophysical methods [1].

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The Salihli geothermal site which is in the center of grapeyards is located in 70 km west of Manisa, 100 km west of Izmir city center (Figure 1). Geothermal energy, produced at the Salihli geothermal site and its surroundings, has been widely used for domestic heating, in about 3000 units, and increasing demand requires exploring new potential fields. For this purpose, geophysical studies may assist in quantifying the geothermal energy potential of the area by delineating subsurface structures.The aim of this study was to delineate the boundaries of geothermal reservoir in Salihli using magnetic method.

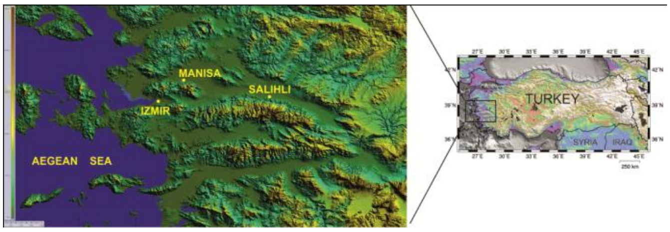

Figure 1. Location of Salihli geothermal area.

Magnetic investigationsin geothermal explorations, generally aim at locating hidden intrusives and possibly estimating their depth, or at tracing individual buried dykes and faults. They may also aim at finding areas of reduced magnetization due to thermal activity. The measurements for local structures such as individual faults or dykes are done on the ground by regular measurements along parallel profiles or in a grid [2]. In a geothermal environment, due to high temperatures, the susceptibility decreases. It is not usually possible to identify with certainty the causative lithology of any anomaly from magnetic information alone. Interpretation of aeromagnetic anomalies over a geothermal area can be further complicated by the presence of magnetic effects caused by volcanic terrain, concealed lavas with a strong magnetisation or reversely magnetised rocks. Conversely, there are examples in the world where hydrothermal demagnetisation causes distinctive negative magnetic anomalies over geothermal fields [3].

In this study, firstly, it is aimed to determine the boundaries of the anomalous structure by using edge detection techniques. The edge detections techniques have been widely used to define the boundaries of the structures both for quantitative interpretation and as a tool for delineating the initial geometric model for inversion processes. Three different edge detection operators were utilized for boundary analysis of the data. After that, 3-D inversion was carried out using the algorithm of [4]. Besides power spectrum method was applied to compare the depth of the structure calculated from inversion.

II. EDGE DETECTION METHODS

A. Analytic Signal

[5] introduced the concept of the analytic signal for magnetic interpretation and showed that its amplitude yields a bell-shaped function over each corner of a 2D body with polygonal cross section. For an isolated corner, the maximum of the bell-shaped curve is located exactly over the corner, and the width of the curve at half its maximum amplitude equals twice the depth to the corner. The determination of these parameters is not affected by the presence of remanent magnetization. Horizontal locations are usually well determined by this method, but depth determinations are only reliable for polyhedral bodies. 3D analytic signal amplitude of a total magnetic intensity (TMI) map, introduced by [6], is widely used in magnetic interpretation as a means of positioning anomalies directly over their sources.

B. Tilt Angle

[7] presented the enhanced local wavenumber method (ELW) for interpreting profile magnetic data. The tilt angle is similar to the local phase, used in the ELW method for profile magnetic data. The local phase uses the sign of the horizontal gradient, whereas the tilt angle uses the absolute value. Recent studies Show that, the derivatives of the tilt angle can provide an automatic estimate of the source location from gridded magnetic data.

C. Horizontal Gradient

The steepest horizontal gradient of a potential field anomaly tends to overlie the edges of the body. Indeed, the steepest gradient will be located directly over the edge of the body if the edge is vertical and far removed from all other edges or sources [8]. The horizontal gradient tends to have maxima located over edges of magnetic or gravity sources. When applied to two dimensional surveys, the horizontal gradient tends to place narrow ridges over abrupt changes in magnetization or density. Locating maxima in the horizontal gradient can be done by simple inspection, but [9] automated the procedure with an algorithm that scans the rows and columns of gridded data.

III. 3-D INVERSION AND POWER SPECTRUM METHODS

The vertical prism is a widely used geometrical model for 3-D interpretation of magnetic anomalies. In general, the magnetized bodies are so close to each other that separation of the anomalies resulting from individual prisms is difficult. Nonlinear optimization techniques such as the Marquardt algorithm [10] may be used for inversion of the magnetic anomalies which result from multiple prisms. As the computing time becomes increasingly high with the number of prisms, attempts have been made to develop efficient algorithms. In this direction, [11] developed a Cholesky decomposition procedure for solution of the normal equations. [4] have presented an efficient method for 3-D modeling of magnetic anomalies. They derived approximate equations for rapid calculation of anomalies and derivatives. Theapproximate equation has been developedwhich treat the prism as a line mass is defined by [4] as;

$$\Delta T(x,y,0) = A\left[\begin{array}{l}(G_1\beta + G_2\alpha)\left(\frac{1}{R_1^3} - \frac{1}{R_2^3}\right) + \frac{G_3C_1\alpha\beta}{(\alpha^2+\beta^2)} \\ -\frac{G_4(C_1\beta^2+C_2)}{(\alpha^2+\beta^2)} - \frac{G_5(C_1\alpha^2+C_2)}{(\alpha^2+\beta^2)}\end{array}\right]$$

(1)

where A, α, β, R_1, R_2, C_1 and C_2 are geometrical; $G_{1,2,3,4,5}$ are physical parameters. The 3-D prismatic model is presented on Figure 2.

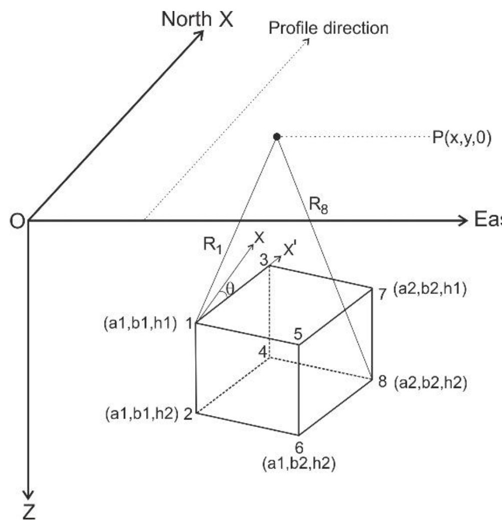

Figure 2. 3-D rectangular prism ([4]).

The average depths of the bodies by which the potential field was created, were resolved by the power spectrum method. For this purpose the digitized potential field data were transformed to the wavenumber domain and the calculated Fourier coefficients were convolved with the filter set to cut down leakages in the resultant energy spectrum. In order to estimate average depths of the basement rock (or thicknesses of the sedimentary layers) in the study area, the power spectrum analyses were applied to the data collected along the profiles using the method of [12].

Complex Fourier transform can be expressed by

$$F(w) = P(w) + iQ(w)$$

(2)

where $P(w)$ is the real and $Q(w)$ is the imaginary part. Amplitude spectrum of $F(w)$ is

$$A(w) = |F(w)| = (P^2 + Q^2)^{1/2}$$
(3)

and energy density spectrum is

$$E(w) = |F(w)|^2 = (P^2 + Q^2)$$
(4)

If the energy density spectrum is obtained using equation (4) and plotted in wavenumber domain after linearizing, then the depth of the body (h) can be calculated from the slope of the data.

$$Slope = -2 \times h$$
(5)

IV. GEOLOGY OF THE AREA

Many regional-scale geophysical studies and several geothermal exploration programs have been carried out in the western Anatolian grabens during the last few decades (MTA-General Directorate of Mineral Research and Exploration of Turkey; TPAO-Turkish Petroleum Corporation) [13]-[14]). Many geothermal test boreholes were drilled in the south part of the graben according to high geothermal potential, being founded around Salihli.

The study area is located in the southernrim of the Gediz Graben. The basement rocks in the area are schists and overlying intercalated marble belonging to the Palaeozoic Menderes Massif. Neogene terrestrial sediments, which are mainly made up of Quaternary alluvium fan deposits, unconformably cover the basement rocks in different facies in the northern and southern parts of the Gediz Graben. The metamorphic rocks consist of gneiss, various schists, marble, quartzite and serpantinite (Figure 3).

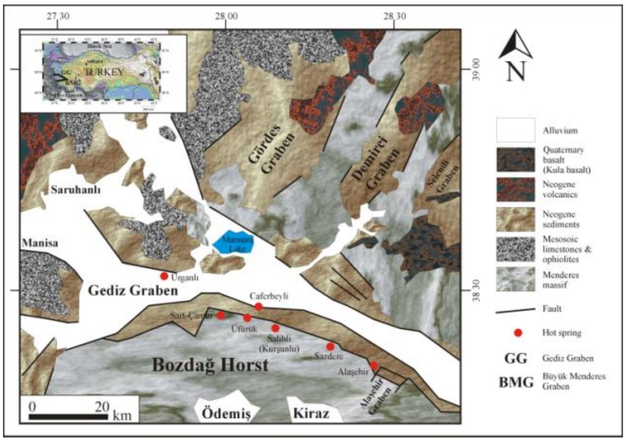

Figure 3. General and structural geology of the Gediz Graben (revised from MTA map, 1964).

V. INTERPRETATION OF MAGNETIC DATA

The total magnetic field data were collected with a profile and station interval of 1 km, at 5400measurement points. The data were mapped and presented in Figure 4. The center rectangular anomaly represents a structure which has a width of approximately 15 km and a length of 18km in S-N direction. According to the geological features and structural characteristics of the area, the high amplitude red color anomaly is considered as the effect of the geothermal area. The dash black rectangle represents the initial model geometry, obtained from the edge detection results, while the black rectangle represents the interpreted model geometry of 3-D inversion. Both for comparison with the 3-D inversion depth and for using as an initial depth parameter for the top of the prism (h1) in the inversion, power spectrum method was applied to A-B section of the data. An automatic algorithm (POMAG) was used for calculation and a depth of 2,1 km was determined for the structure.

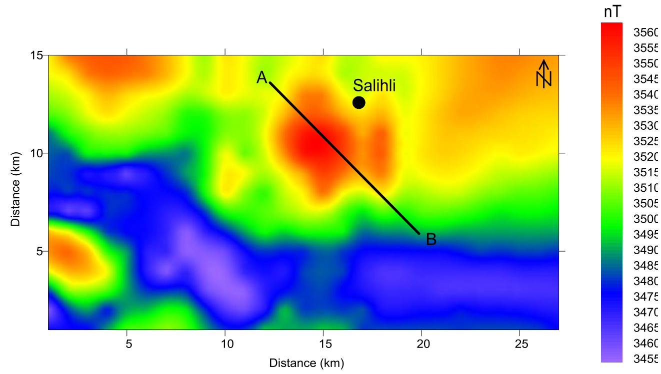

Figure 4. Total magnetic field map of the study area. Black dash line indicates initial model, black rectangle indicates interpreted model and A-B section.

After collecting and mapping the data, Analytic signal, horizontal gradient and tilt angle boundary analysis methods were utilized to data respectively, to obtain precise geometry of the anomalous structures. Result of Analytic signal method presented the boundaries of the anomalous structure with red color anomalies (Figure 5) and possible boundaries of the structure is demonstrated with black dash lines. The result of horizontal gradient method is presented on Figure 6. The boundaries on the west and south parts of the anomalous structure are clearly identified with this method. The result of tilt angle studies were mapped and presented on Figure 7. Although the results were more complicated than the other two methods, boundaries of the temple and the pedestal are identified. the theta map study is presented on Figure 7. Again, the boundaries were indicated with black dash lines for determining the initial prismatic model geometry, used in 3-D inversion.According to continuity and persistance of the red color anomalous boundaries, the best result is achieved from Analytic signal method.

Considering the outcomes of the boundary analysis studies, geometrical initial parameters of a prismatic model was determined. Initial geometrical and physical parameters used in the inversion process are indicated in Table 1. Relatively small change in the geometrical values support that the initial model represents the actual structure successfully. Also calculated top and bottom depths of the structures are in concordance with the depths calculated by using power spectrum method. Both initial and interpreted models are presented on Figure 8.

Table 1. Initial and interpreted model parameters for a 3-D prismatic body.

Prism No	Model	a_1 (km)	a_2 (km)	b_1 (km)	b_2 (km)	h_1 (km)	h_2 (km)	I_O (Deg)	D_O (Deg)	Θ (Deg)	EI (CGS)	Iteration Number
1	Initial Model	12,8	16,7	8,2	11,3	2	6	57	3	0	0,005	11
	Interpreted Model	11,8	15,6	10,4	12,6	2,4	4,1	44,9	0,9	7	0,0082	

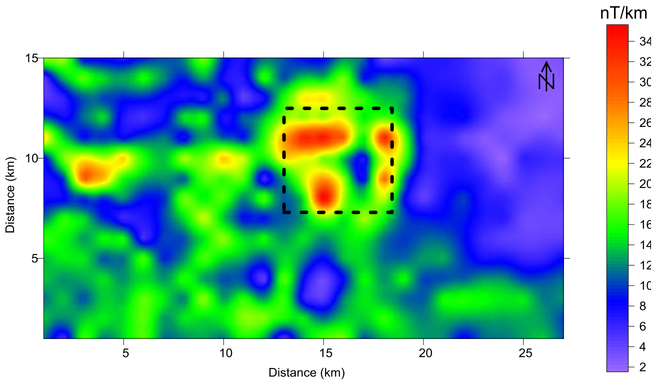

Figure 5. Analytic signal map of the study area.

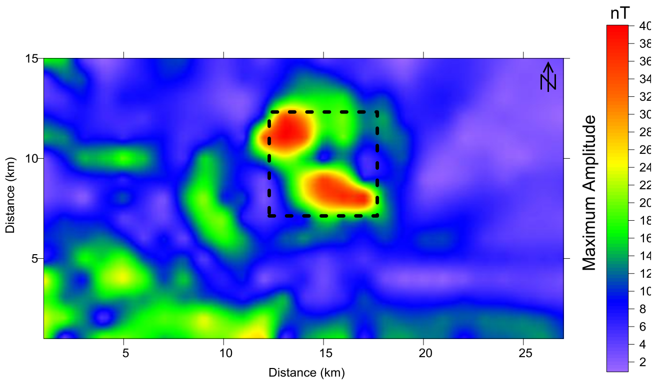

Figure 6. Maximum horizontal gradient map of the study area.

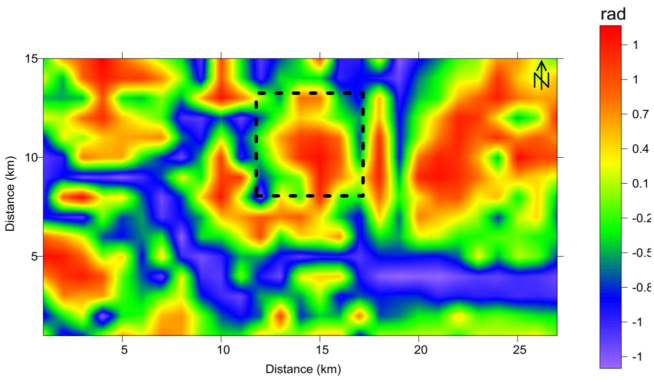

Figure 7. Tilt angle map of the study area.

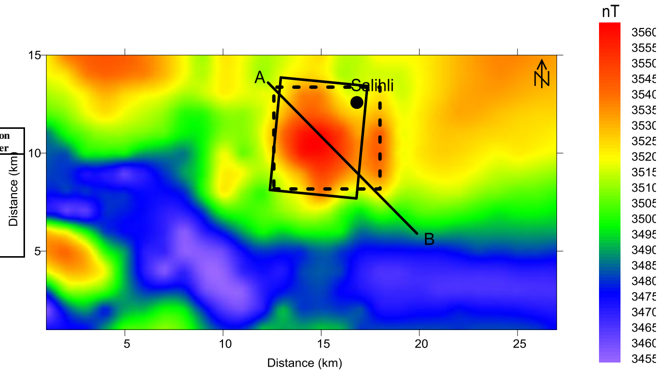

Figure 8. Total magnetic field anomaly map of study area, initial models indicated with black dash lines, calculated models indicated with black lines.

VI. CONCLUSION

A regional magnetic investigation in Salihli district of city of Manisa (Turkey) carried out to determine the geometry of the geothermal potential. After mapping the data, three edge detectors were applied in order to define the initial model for inversion. Analytic signal and horizontal gradient methods presented similar results but the outcome of the tilt angle study was not satisfying, while it was complicated and hard to interpret. The power spectrum method is very easy to perform and it supported an idea about the depth of the anomalous structure. The calculated values from inversion and power spectrum methods yielded similar results as 2,4 km and 2,1 km respectively. It is recommended that detailed investigations should be performed and test drillings should be opened in the south and southwest of the Salihli city center.

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